Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

The Mu2e Experiment at Fermilab : Exploring the Unknown

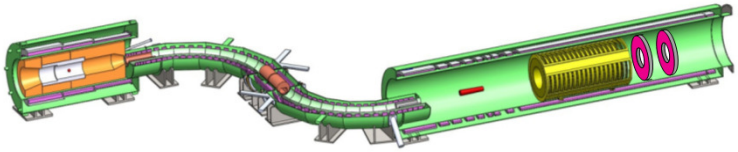
Ray Culbertson

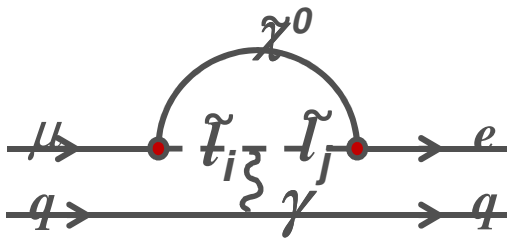
BLV 2015

26 Apr 2015

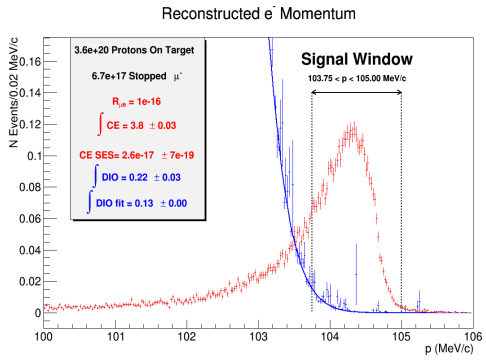
Mu2e in One Slide

- Search for new physics in
  μ N$\rightarrow$ e N





- The mu2e experiment



- Controlling backgrounds

- Detector details and status

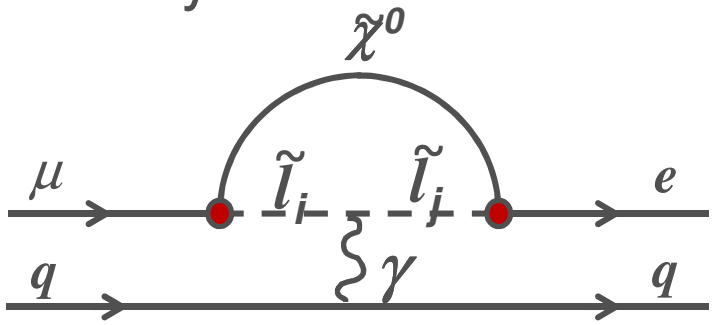
- Schedule

The Mu2e Idea

Why this Experiment

- Search for CLFV
- $\mu^- + N \rightarrow e^- + N$

- Decay of μ to e is very(!) small in SM plus neutrino mass
- It does happen in many New Physics scenarios



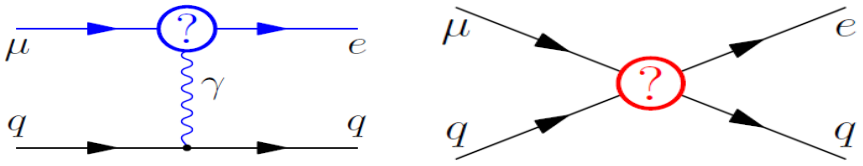
W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

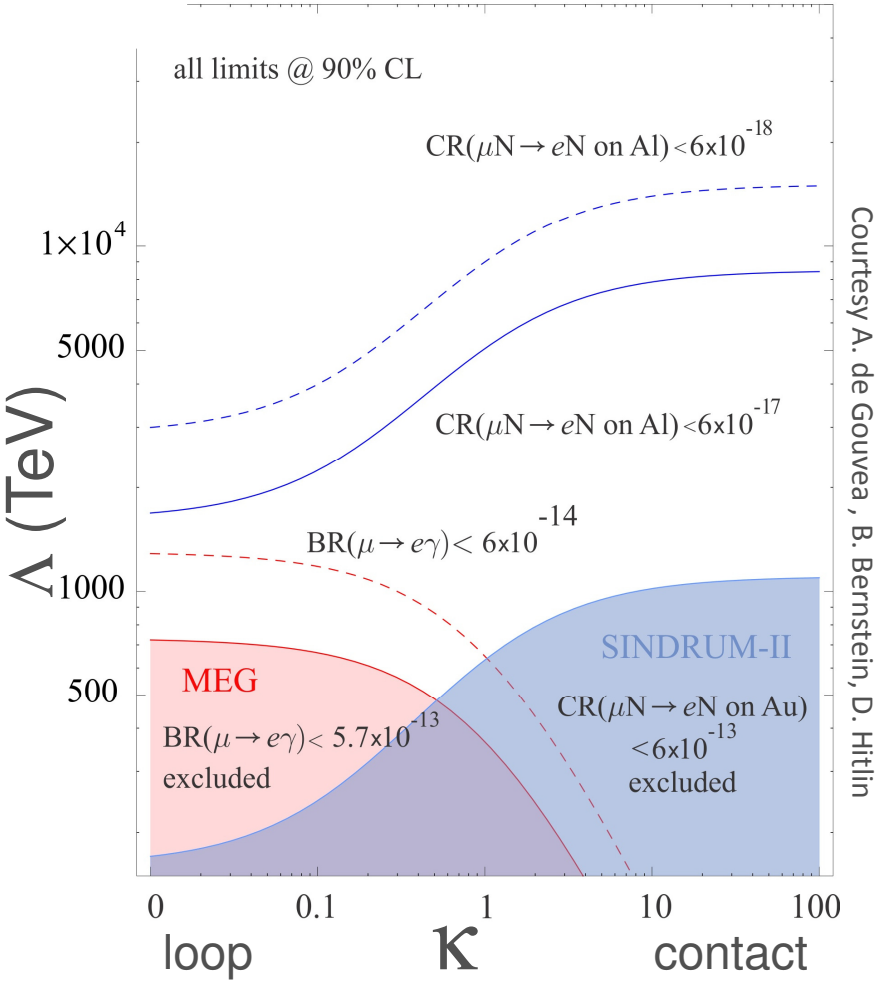
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Why this Experiment

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$



- Different from MEG expt. (μ→eγ) and complementary
- Having both measurements will help define the N.P. scenario
- Sensitive to N.P. scales far beyond LHC !

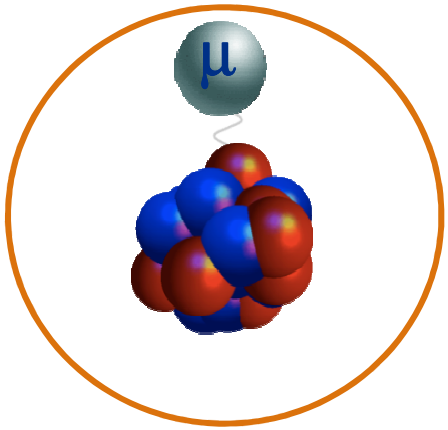


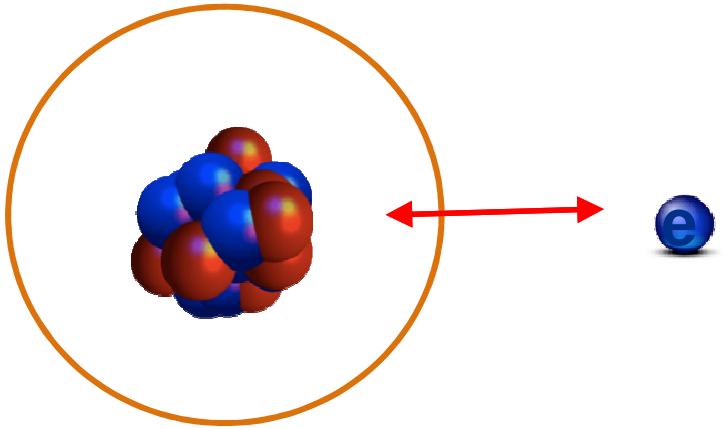
Courtesy A. de Gouvea , B. Bernstein, D. Hitlin

Fermilab

The New Physics Signal

- Muons captured on Al nucleus
- 864ns lifetime
- Nucleus+μ^- is a system, decays to nucleus+e^-
- Conversion decays produce mono-energetic electrons





$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\rm recoil} \\ &= 104.973 \text{ MeV} \quad \text{(for Al)} \end{aligned}$$

- Mu2e measures:

$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z,N) \to e^- + A(Z,N)]}{\Gamma[\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N+1)]}$$

Mu2e by the Numbers

- In a 3-year run of …
  - 10^{20} protons on target
  - 10^{18} stopped muons
- Expected single-event-sensitivity $R_{\mu e} = 2.9 \times 10^{-17}$
- Target limit (if no signal): $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL
- Factor 10^4 improvement over the current limit!
  - $R_{\mu e} < 7 \times 10^{-13}$ @ 90% CL (on Au)
  - SINDRUM II (W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006))

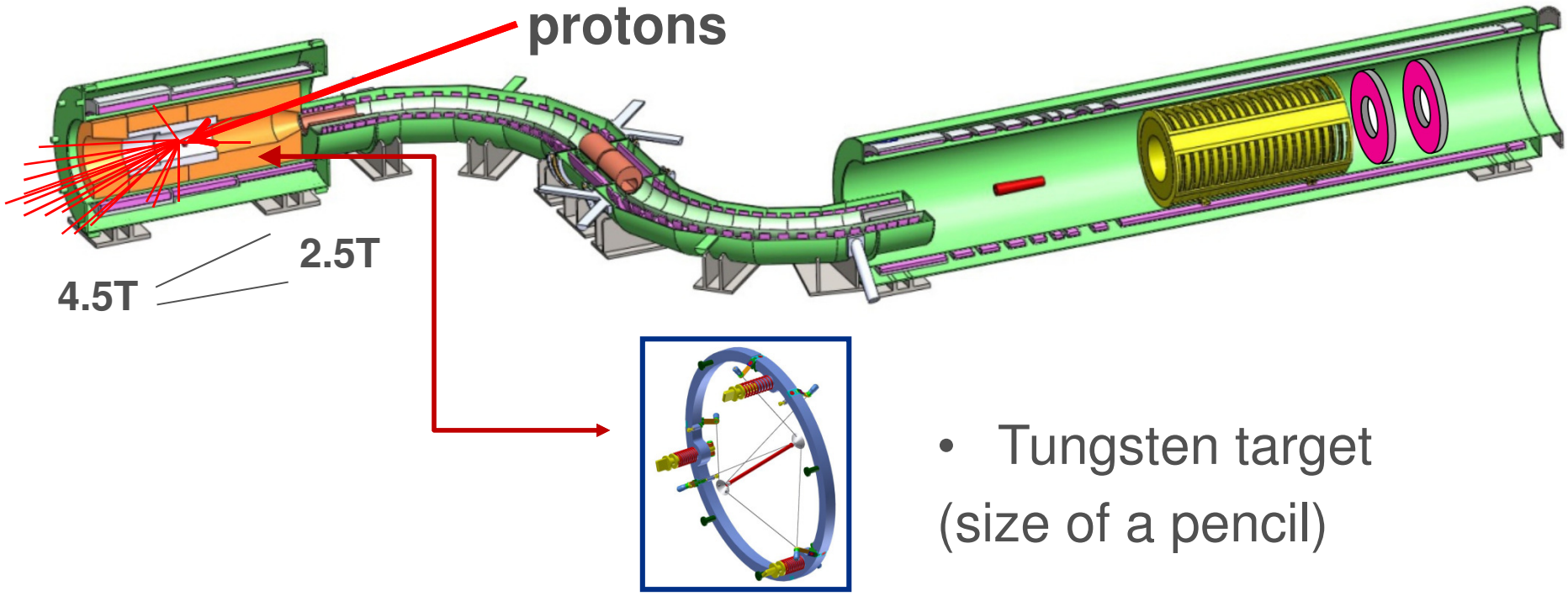
3

- Expected discovery sensitivity: $R_{\mu e} >$ few $\times 10^{-16}$
  - Covers broad range of new physics theories!
  - LHC-scale SUSY will be many events, an obvious signal!

The Experiment

The Experimental Concept

- 8 GeV proton beam strikes target
- Graded field pushes pions and muons into Transport Solenoid
- This drawing represents 25 m end-to-end

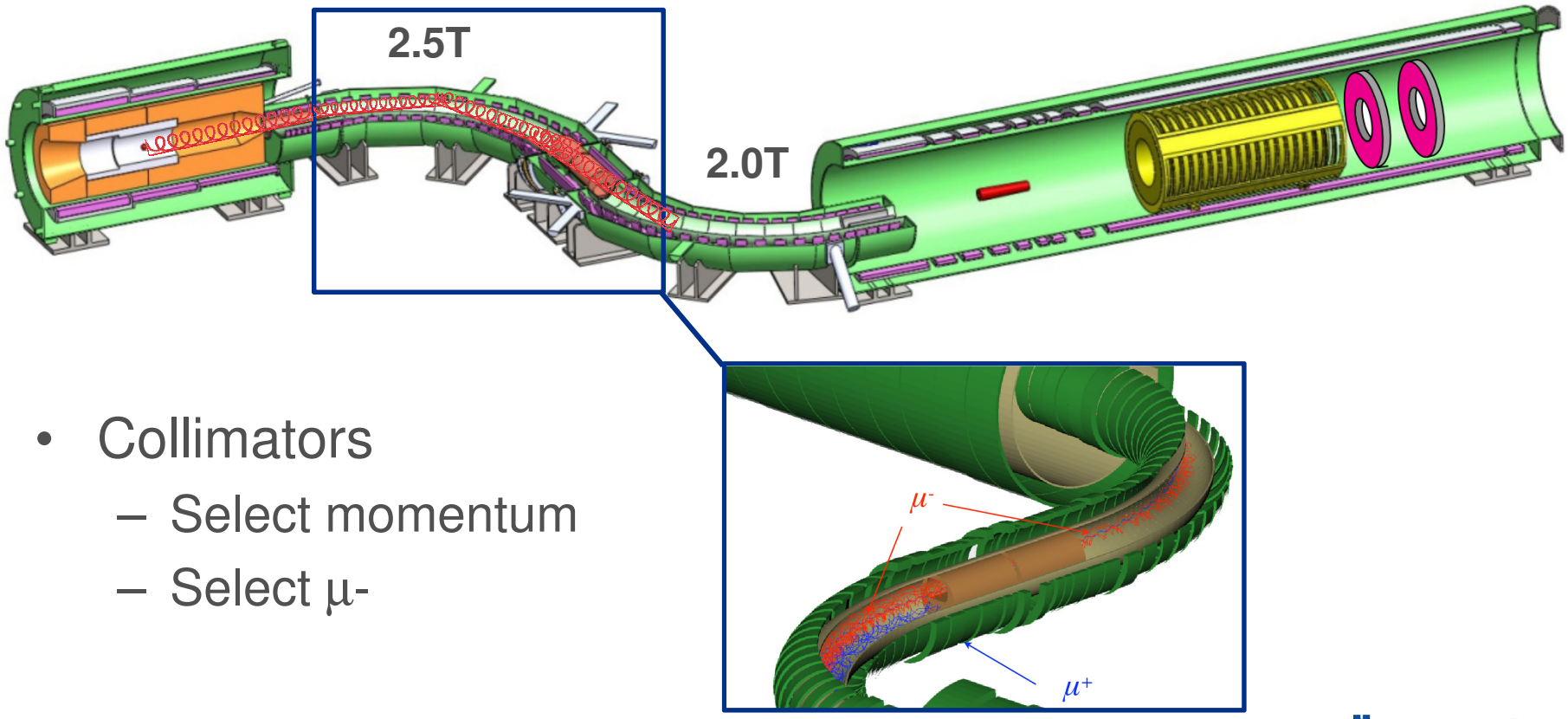


- Tungsten target

(size of a pencil)

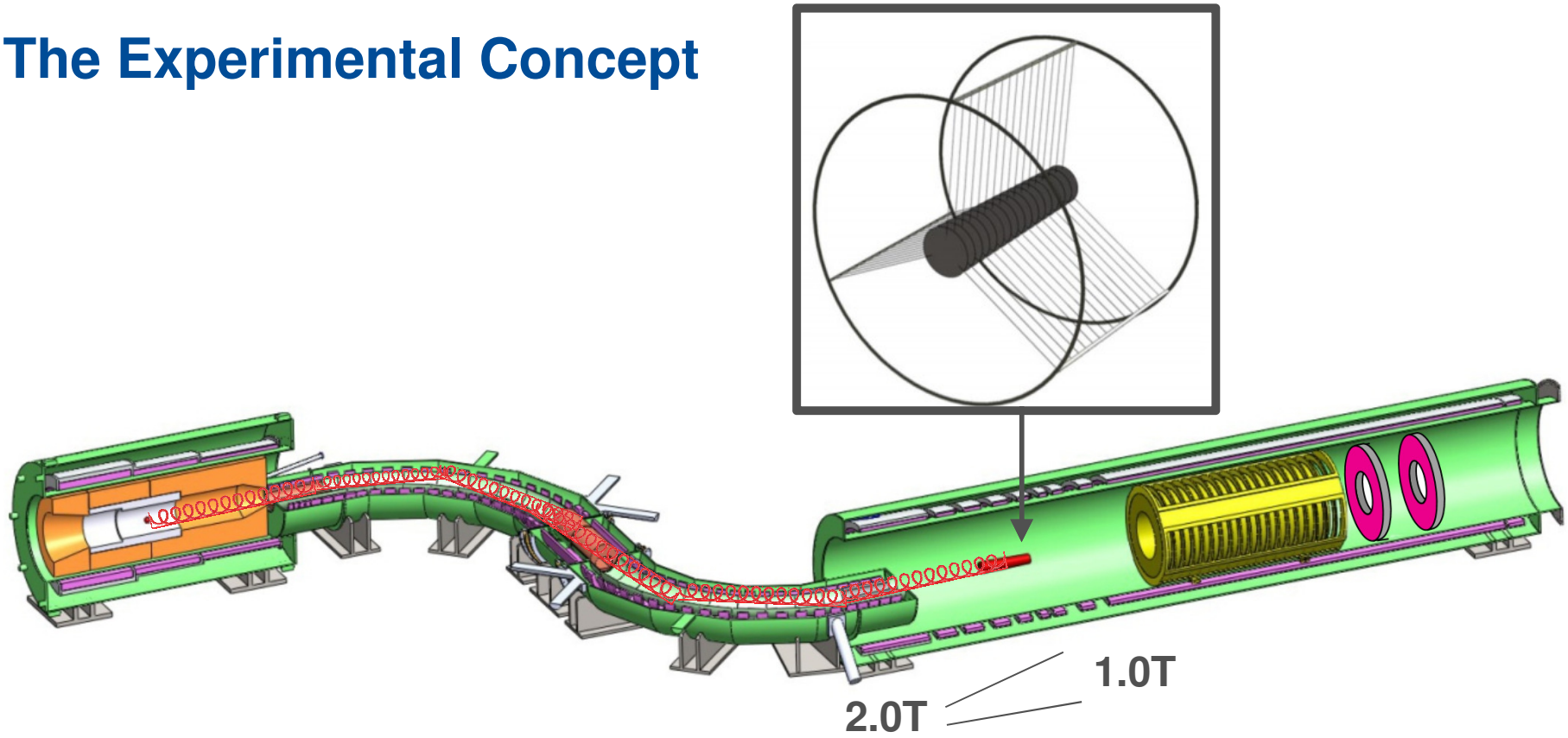
The Experimental Concept

- Transport solenoid channel
  - Allow pion decay
  - S-shape to remove neutrals



- Collimators
  - Select momentum
  - Select μ-

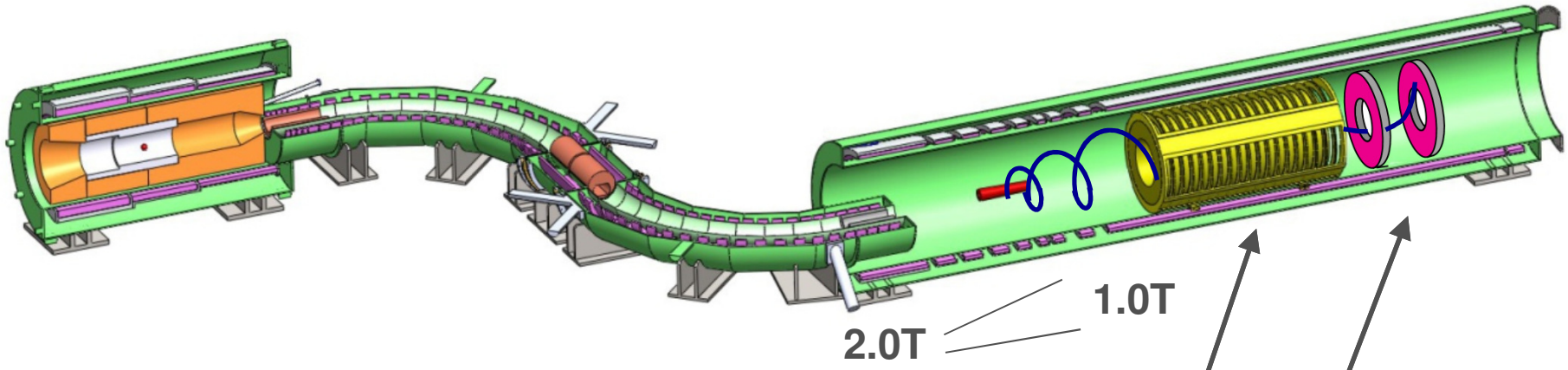
The Experimental Concept



- Stopping Target foils - muons range out, stop
- Stopped μ^- fall into orbit around Al nucleus

The Experimental Concept

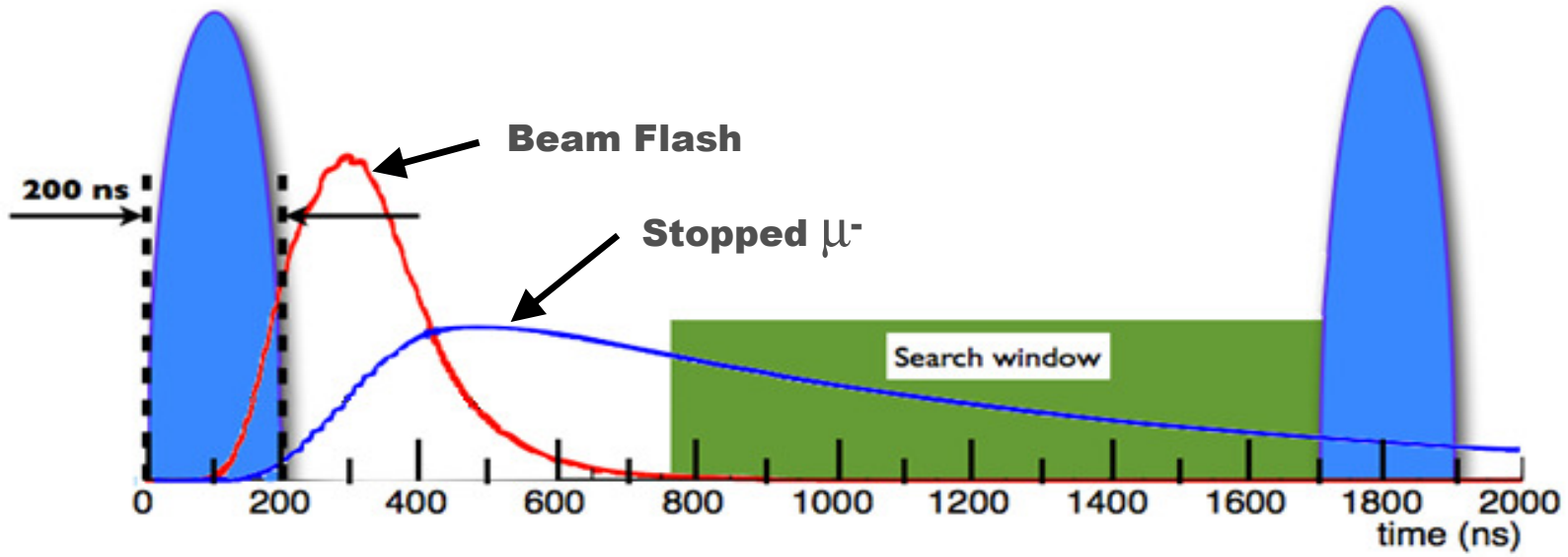
- Conversion events would produce a 105 MeV electron
- Graded magnetic field pitches signal electrons towards detector and background into the uninstrumented region



- Momentum measured in tracker
- Electron ID confirmed in calorimeter

Pulsed Muon Production

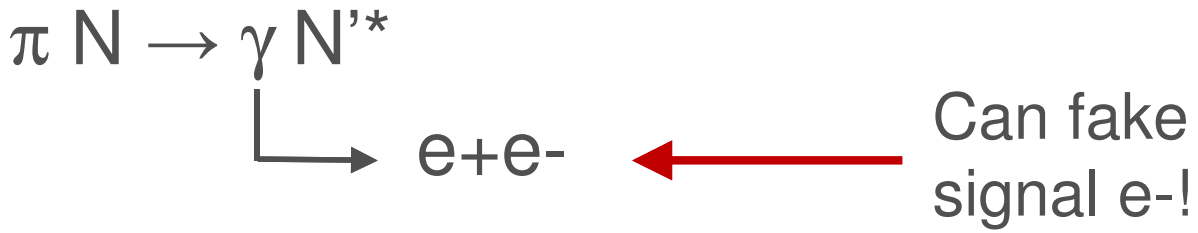
- Alternate:
  1) beam on target – produce and stop muons (detector blinded)
  2) observe stopped muon decays
- Extinction of beam in search window is critical, $<10^{-10}$
  - Special beamline design and monitor



The Backgrounds

Backgrounds 1 – *Pions*

- Pions produced in beam pulse also get captured
- 2% undergo Radiative Pion Capture (RPC)

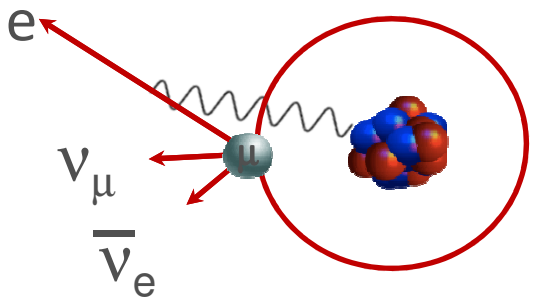


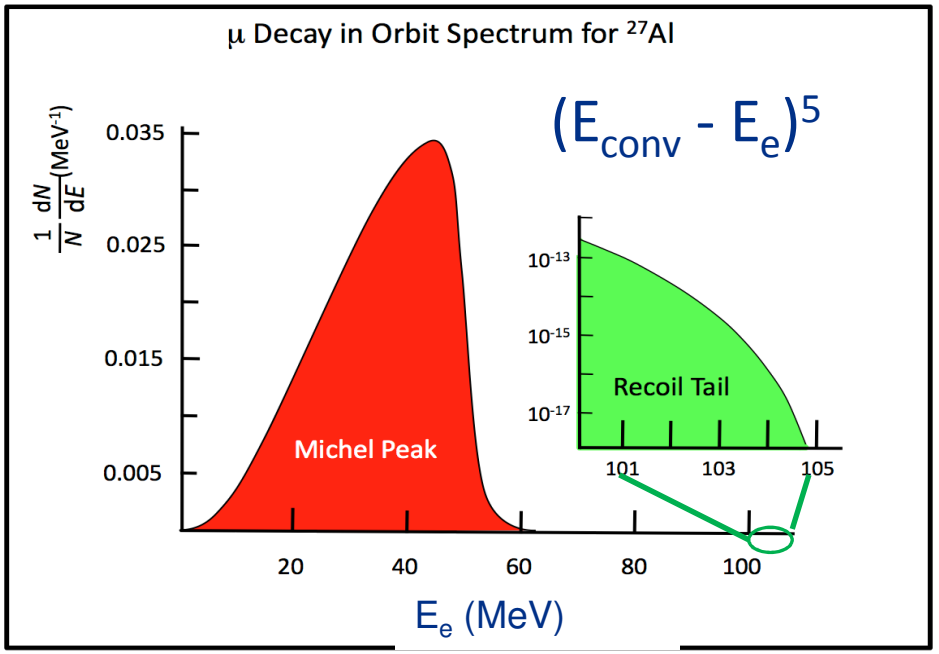
- Also π, μ decays-in-flight and e- from production target

- Start the search window when these are small enough…

Backgrounds 2 – Muons

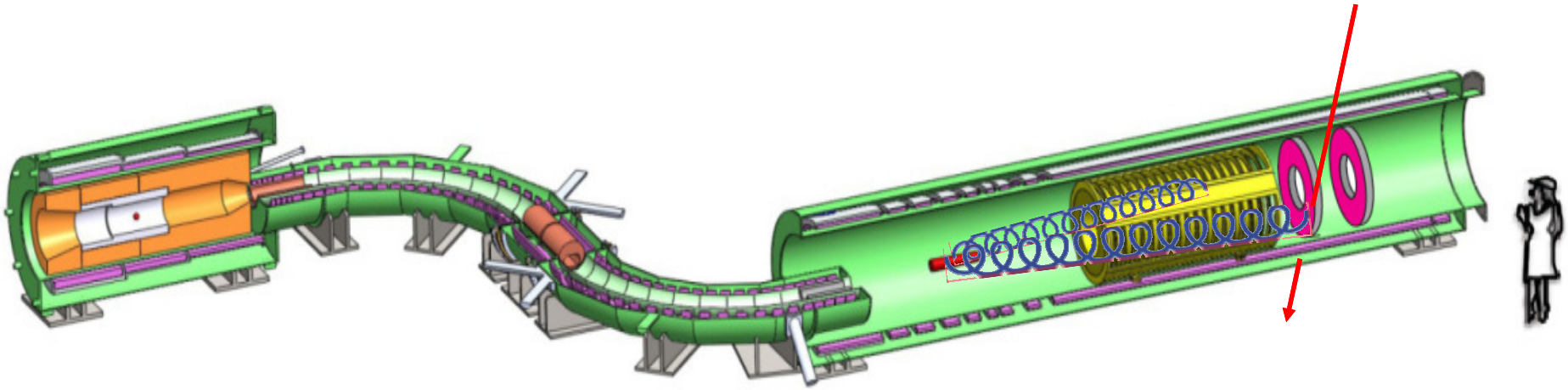
- Decay in Orbit (DIO)
  - 39% of stopped muons
  - Normal muon decay mode
  - Long tail with tiny phase space appears in the signal region
- The largest intrinsic b.g.
  - Scales with signal
- Muon Capture
  - μ N $\rightarrow \nu$ N'*
  - 61% of stopped muons
  - Not a background..



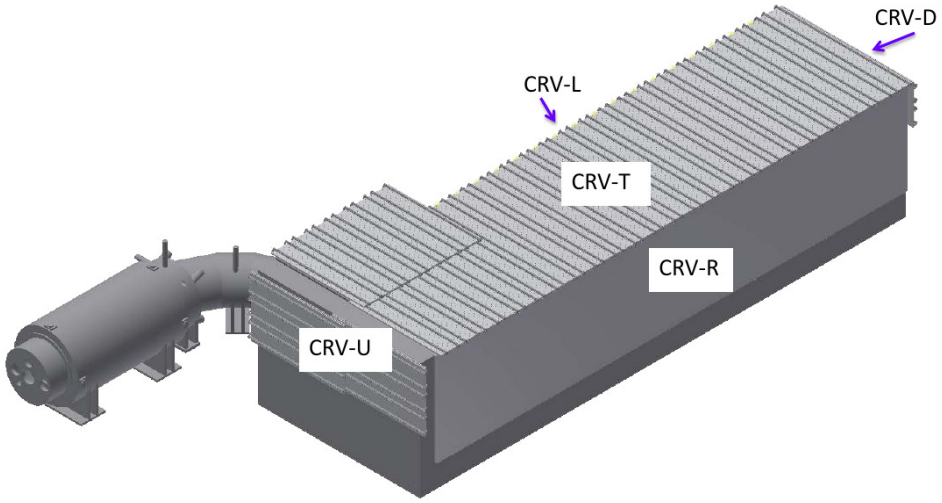


Fermilab

Backgrounds 3 – Cosmic Rays

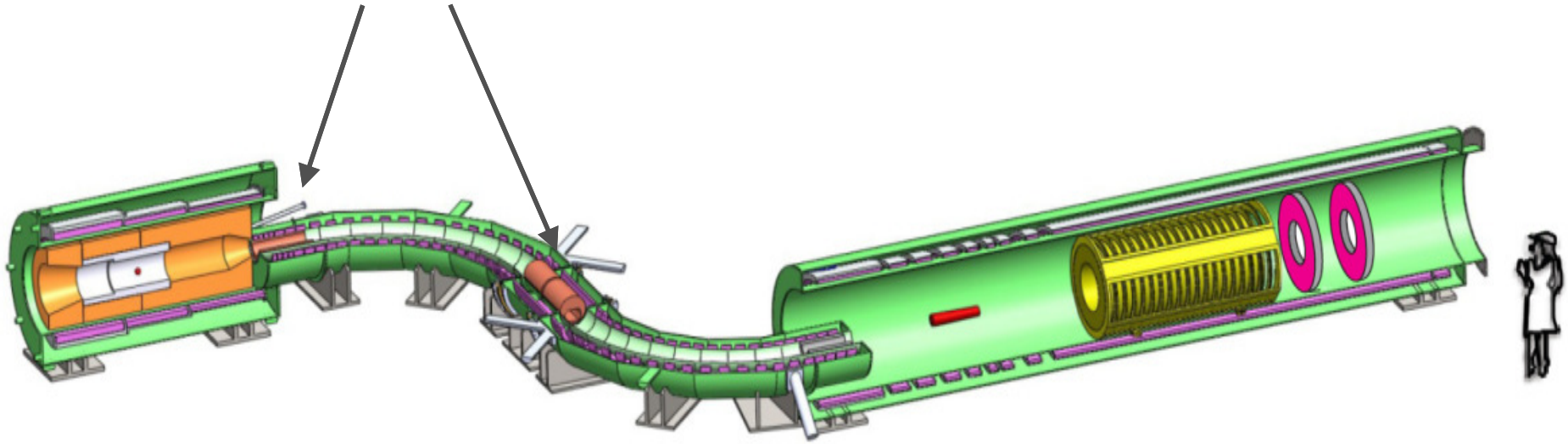


- Cosmic ray interactions can produce electrons
- Would see 1/day – way too high!
- Cosmic ray veto system must reject 99.99%



Backgrounds 4 - Antiprotons

- Proton beam is over threshold for anti-proton production
- Accepted – they're negative, long-lived
- Annihilate into "energetic" multi-particle states - pions, photons
- Reduced with two thin absorbers



Background Totals

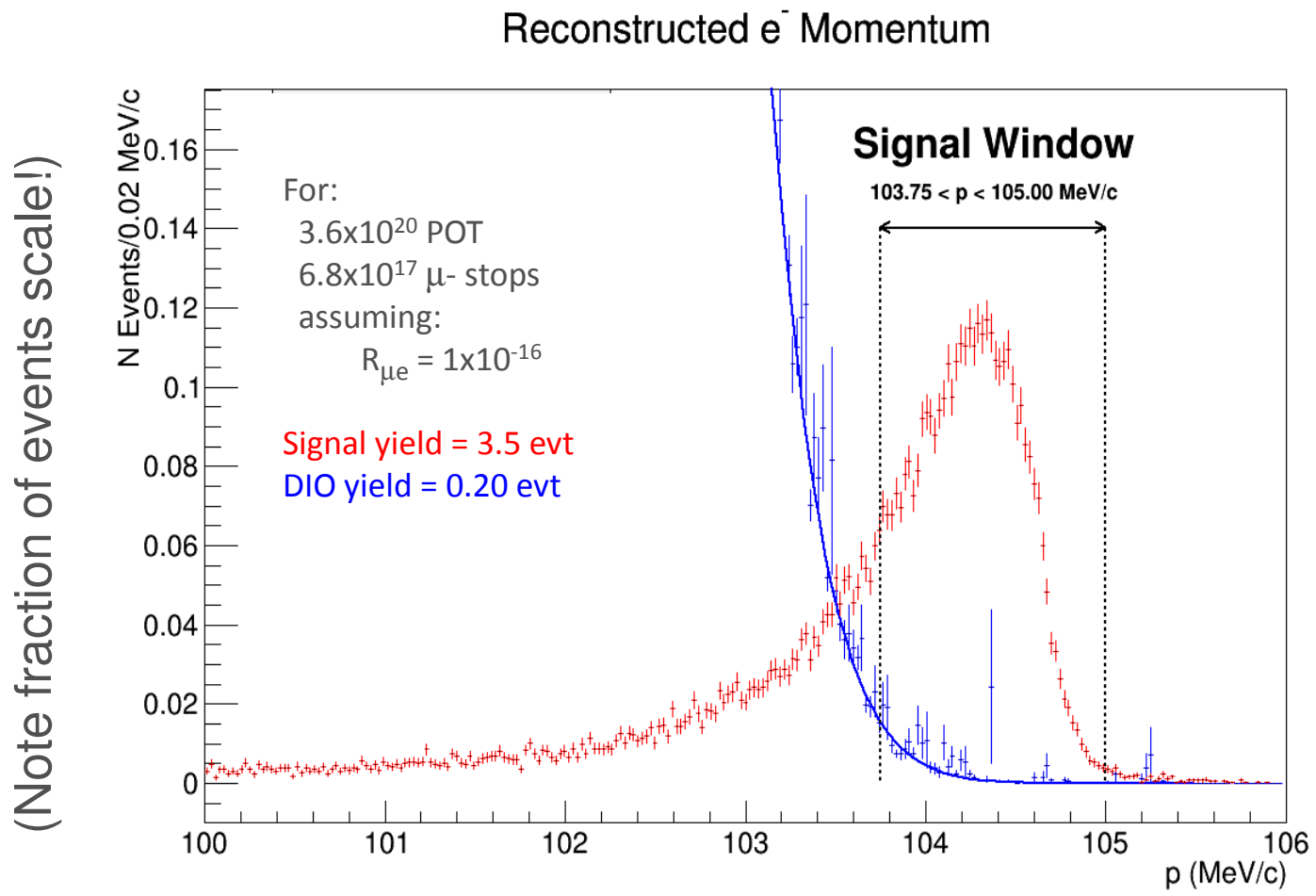
- Background counts expected in 3.6×10^{20} POT

Category	Background process	Estimated yield (events)	
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092	54%
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$	
Late Arriving	Pion capture (RPC)	0.023 ± 0.006	
	Muon decay-in-flight (μ-DIF)	<0.003	
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$	
	Beam electrons	0.003 ± 0.001	
Miscellaneous	Antiproton induced	0.047 ± 0.024	13%
	Cosmic ray induced	0.092 ± 0.020	25%
	Total	0.37 ± 0.10	

- DIO must be managed!
- What does this look like in the detector?

The Big Analysis Plot

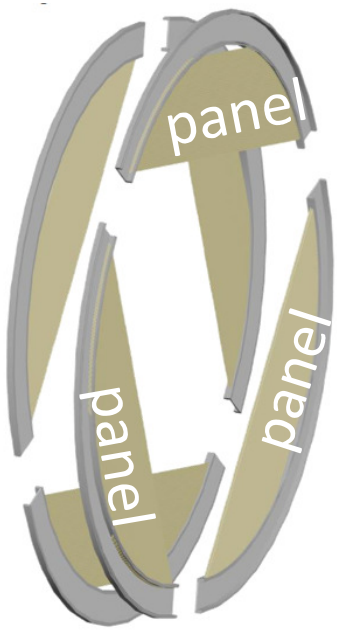
- Require high efficiency, but also low mass, good resolution!

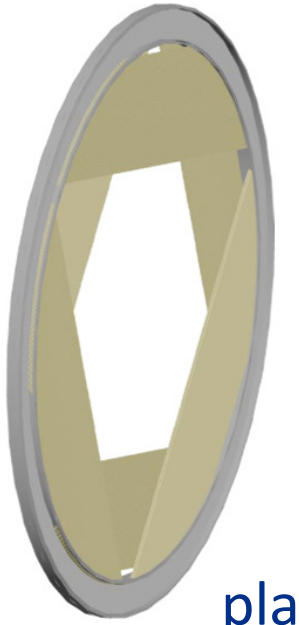


The Detector

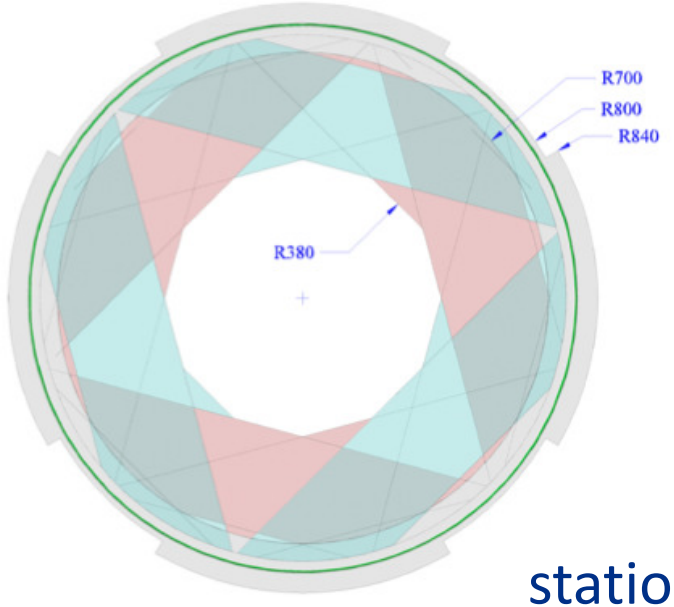
Tracker

- 20K 5 mm straw tubes
- Al, Au-coated 15μm Mylar
- 80/20 Ar/CO_2
- TDC and ADC readout





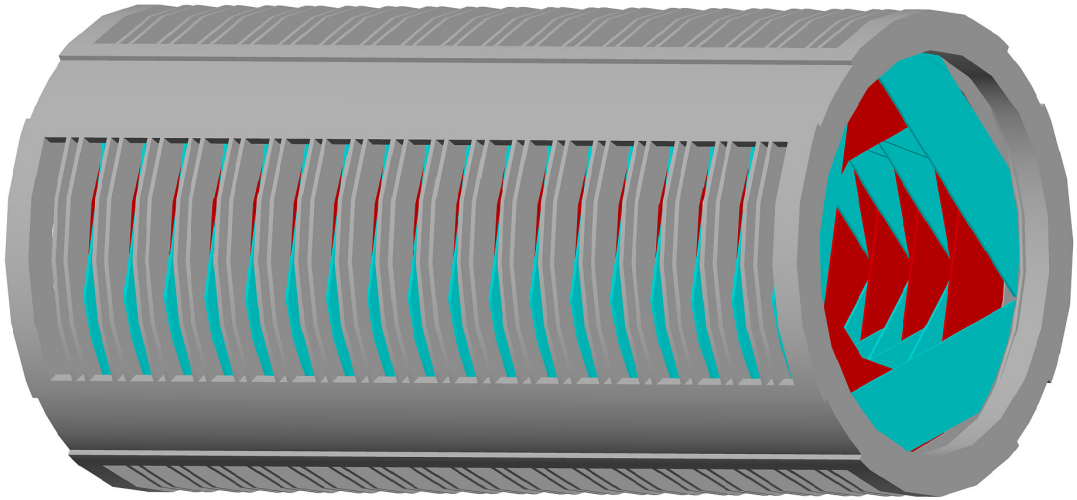
plane

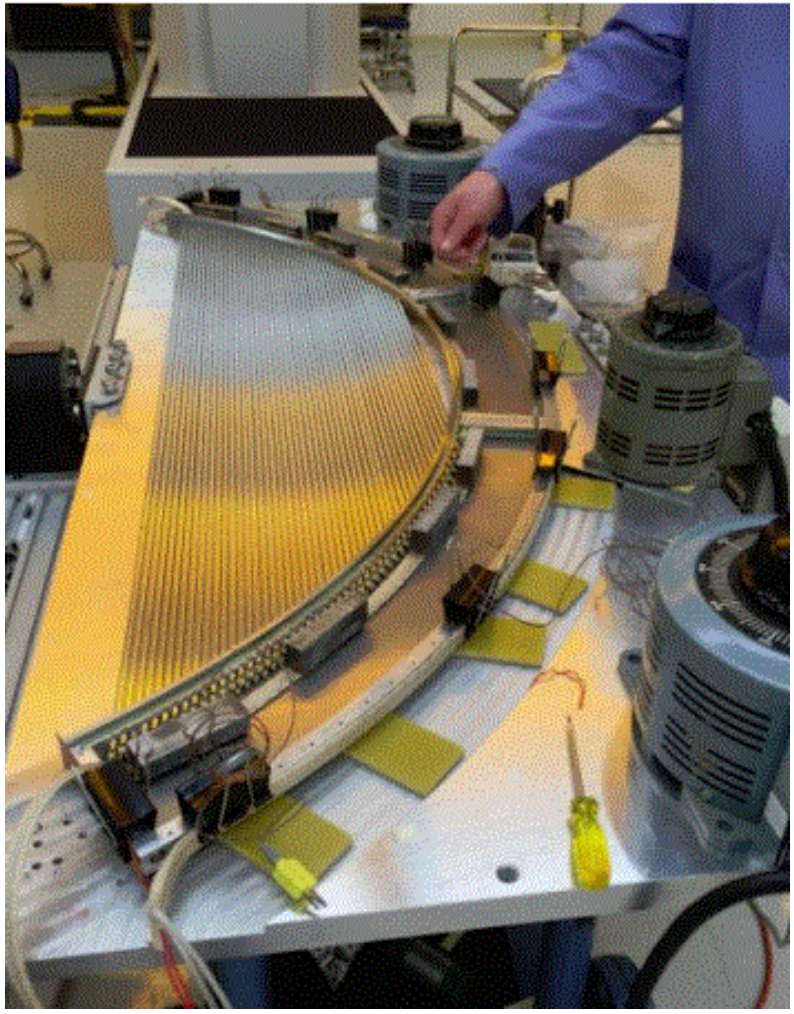


station

Tracker

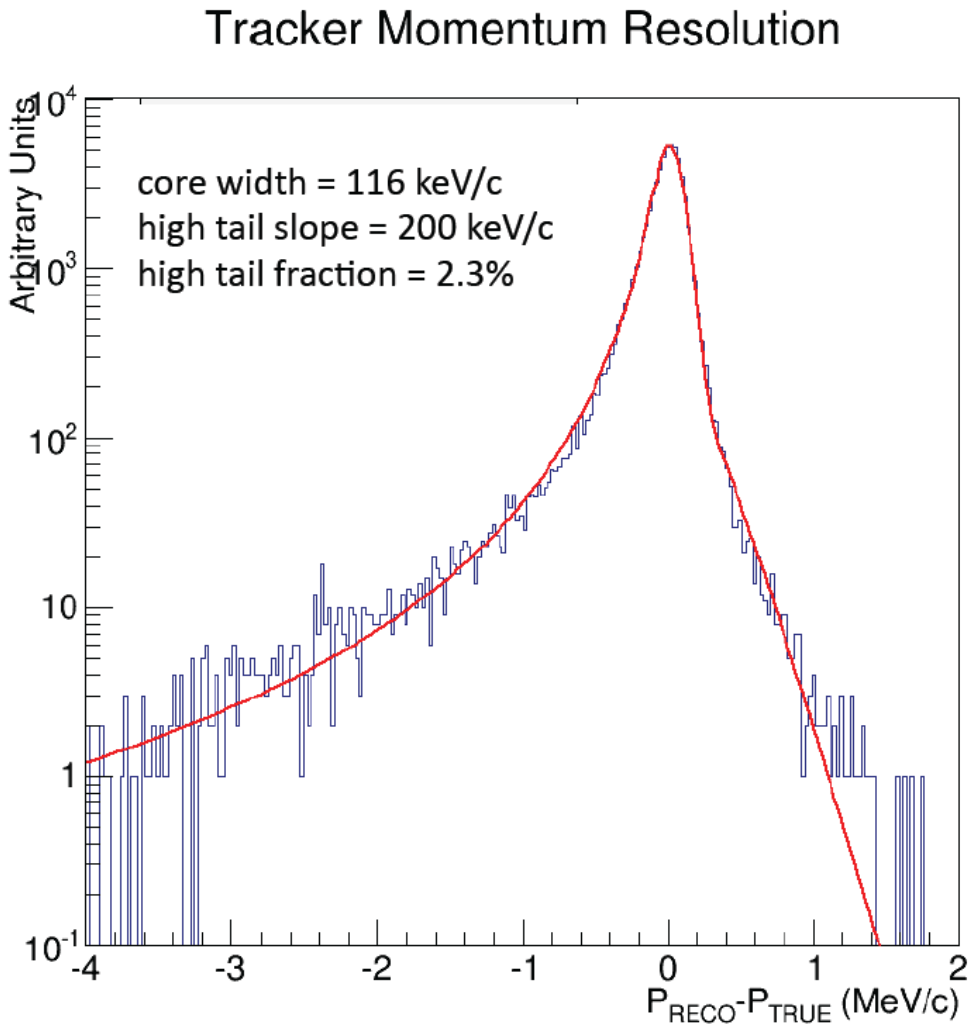
- 18 stations in 3 m cylinder
- ~ 40 hits per track
- 100 μm hit resolution



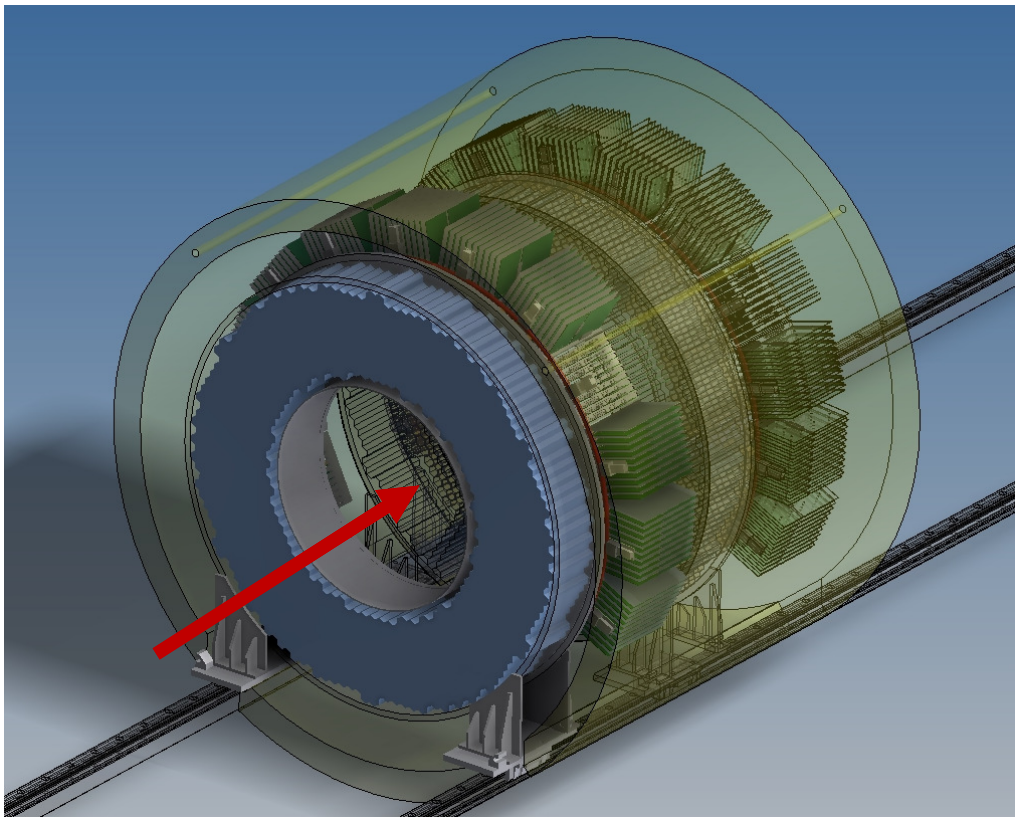


Tracker Performance

- Meets all physics requirements
- Total efficiency 9.2%
  - mostly acceptance
- Resolution 116 keV
- Robust against rate increases
- Low end is energy loss (lowers efficiency)
- High end tail smears DIO into signal region



Calorimeter



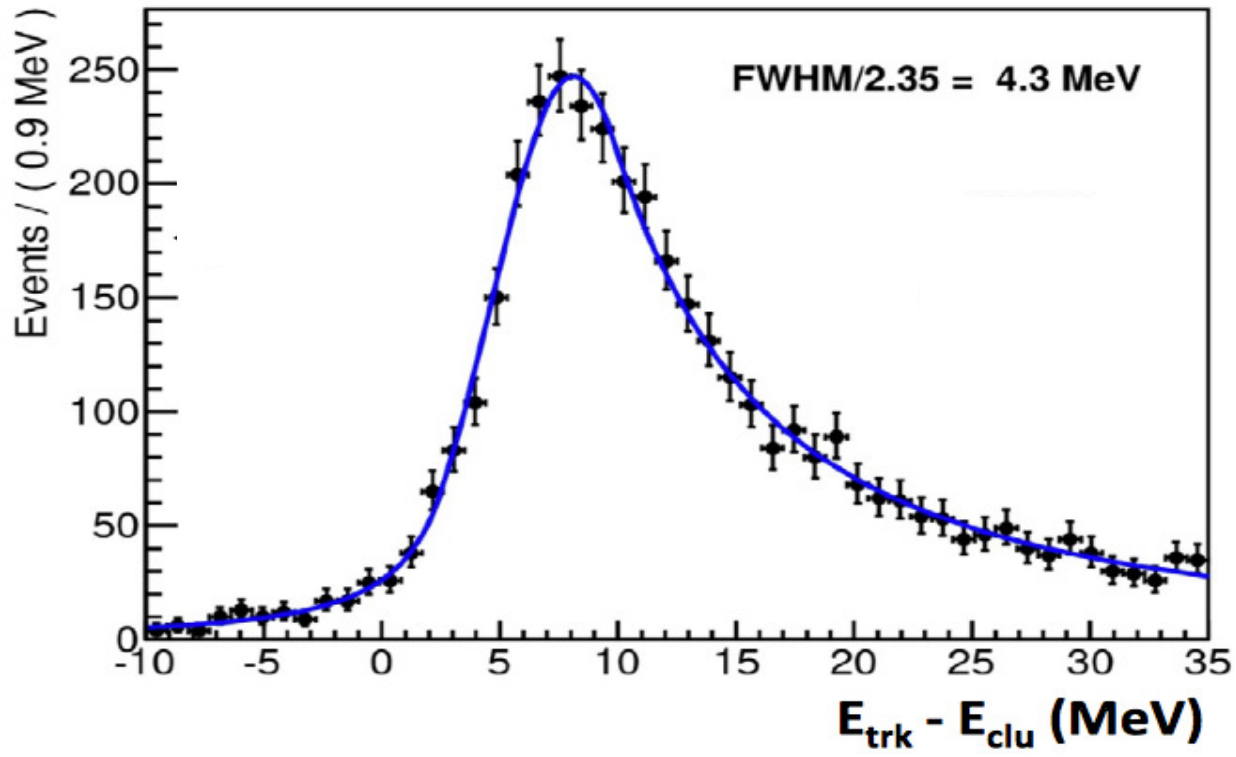
- Two disks behind tracker
- 36-70 cm radius
- BaF_2 Crystals
  - Radiation hard
  - Non-hydrodscopic
- 1600 crystals
- 3x3x20cm (10 rad. len.)
- Read out by two

APD per crystal

- Crystal samples, electronics, in testing now

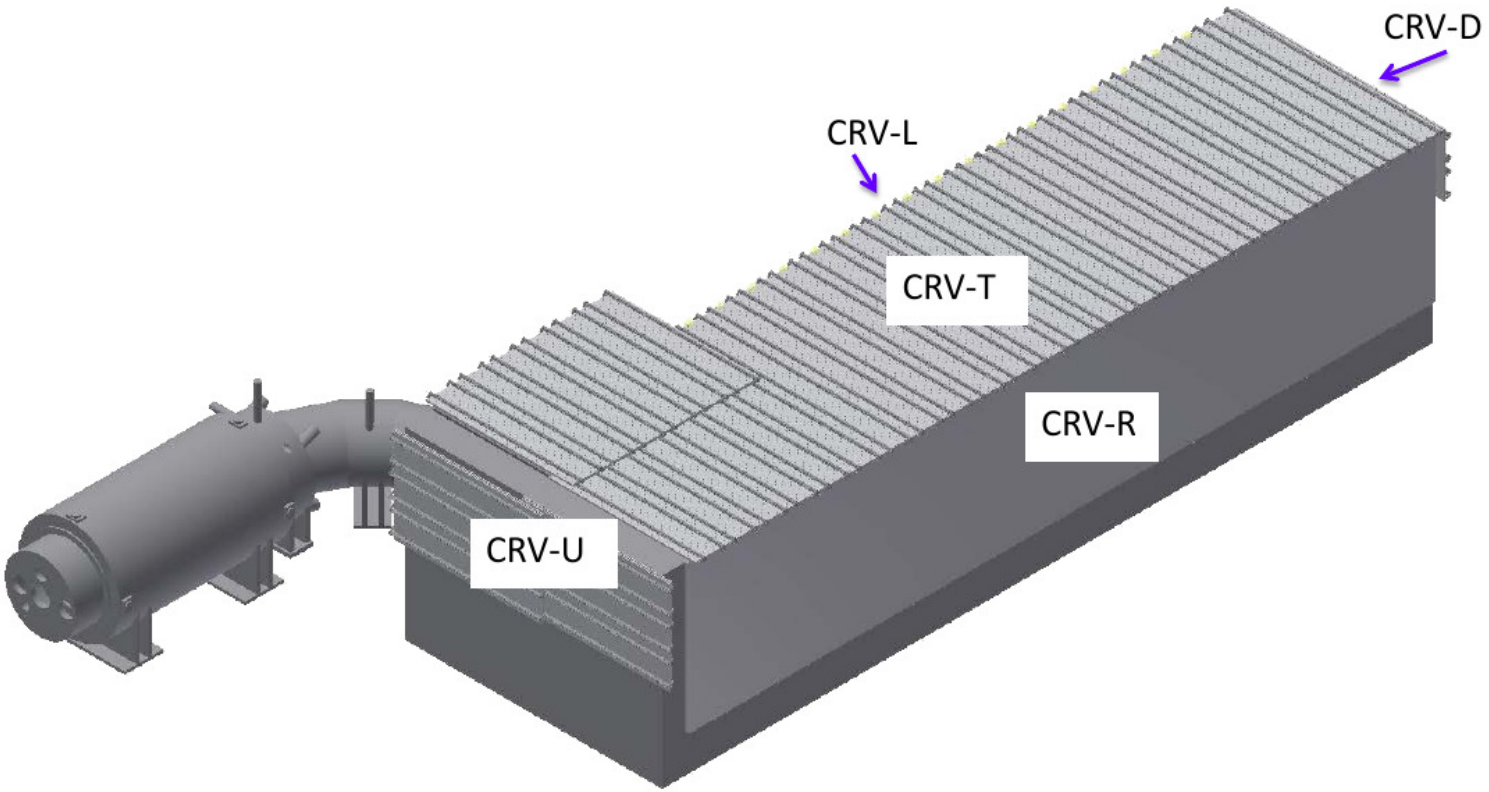
Calorimeter

- Provides independent
  - Timing (0.5ns)
  - Energy (5%)
- Rejects
  - Pions, muons
  - Cosmic rays



Cosmic Ray Veto

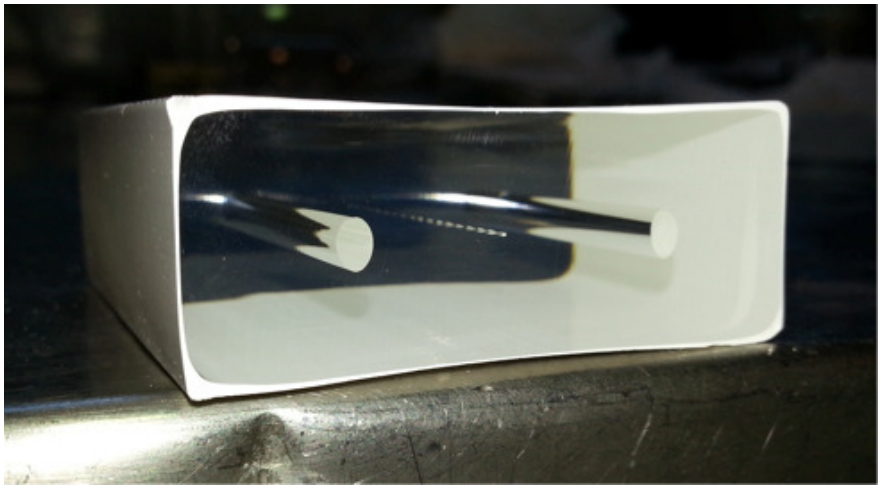
- Covers entire detector and half of transport solenoid

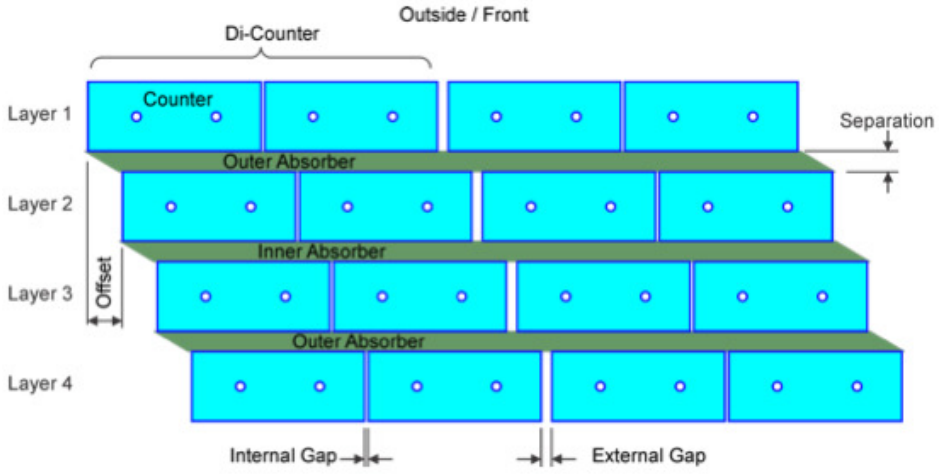


- Dirt, concrete overburden helps..

Cosmic Ray Veto

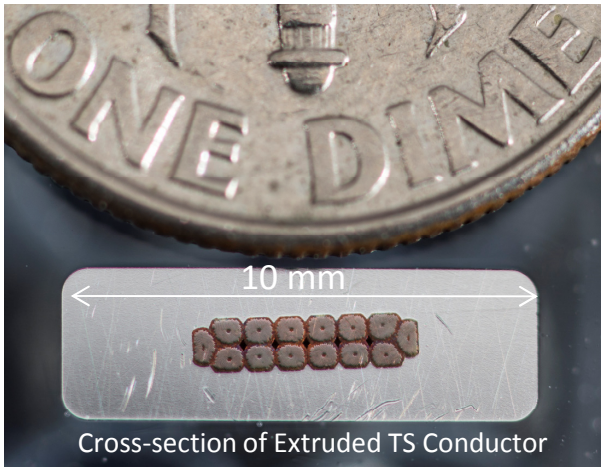
- 4 layers of scintillator bars 5x2 cm, 3-6 m long
- Staggered to cover gaps
- 2 WLS fibers per bar, read out both ends with a SiPM
- Achieved 99.4% (in only one layer, in test beam)
  - meets requirements!

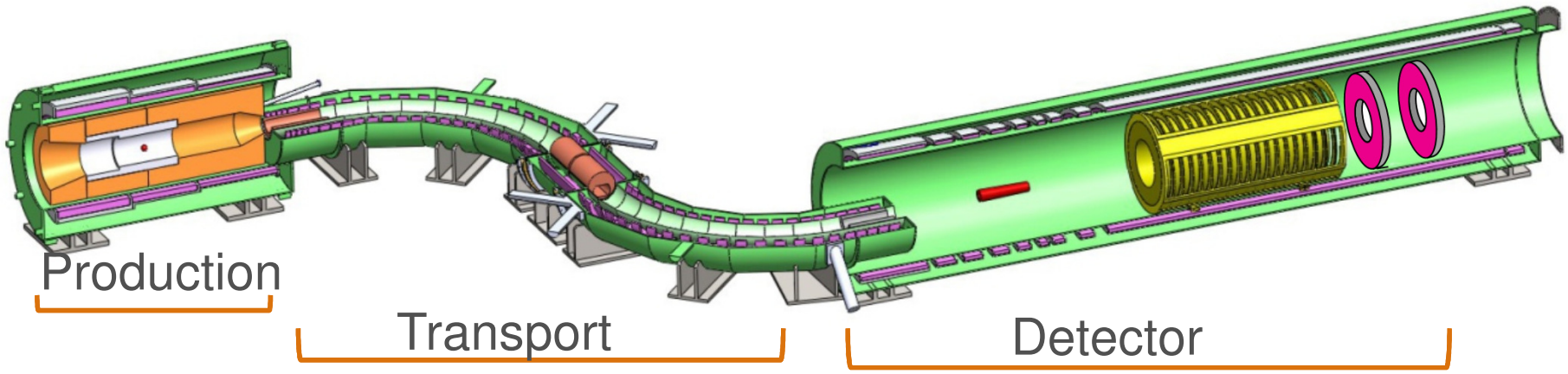




Magnets

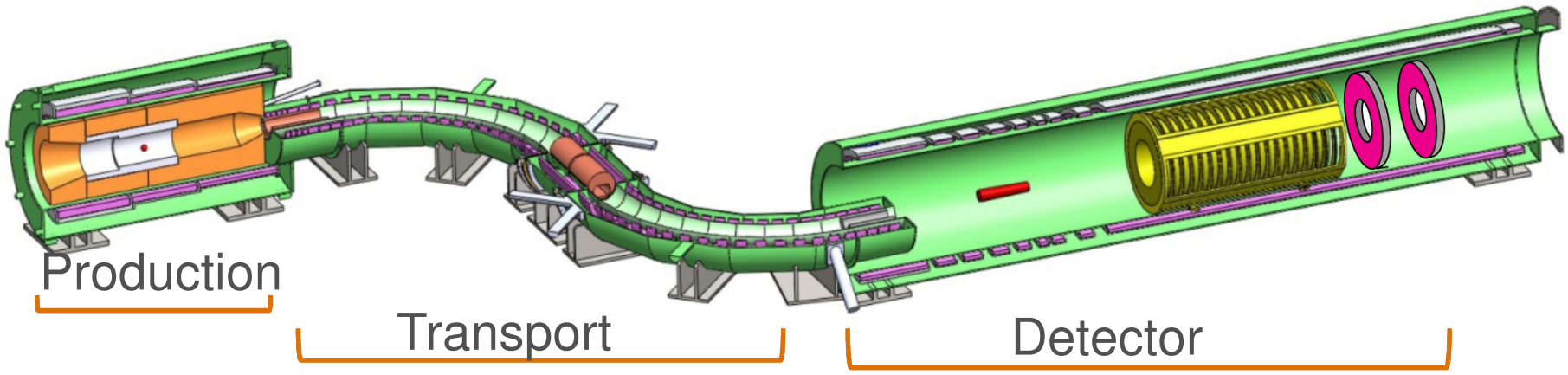
- Are the heart of mu2e!
- NbTi superconducting
- Designs are well-advanced
- Conductors in production (75km)!





Magnets

	PS	TS	DS
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	50	11
Conductor (km)	10	44	15
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8



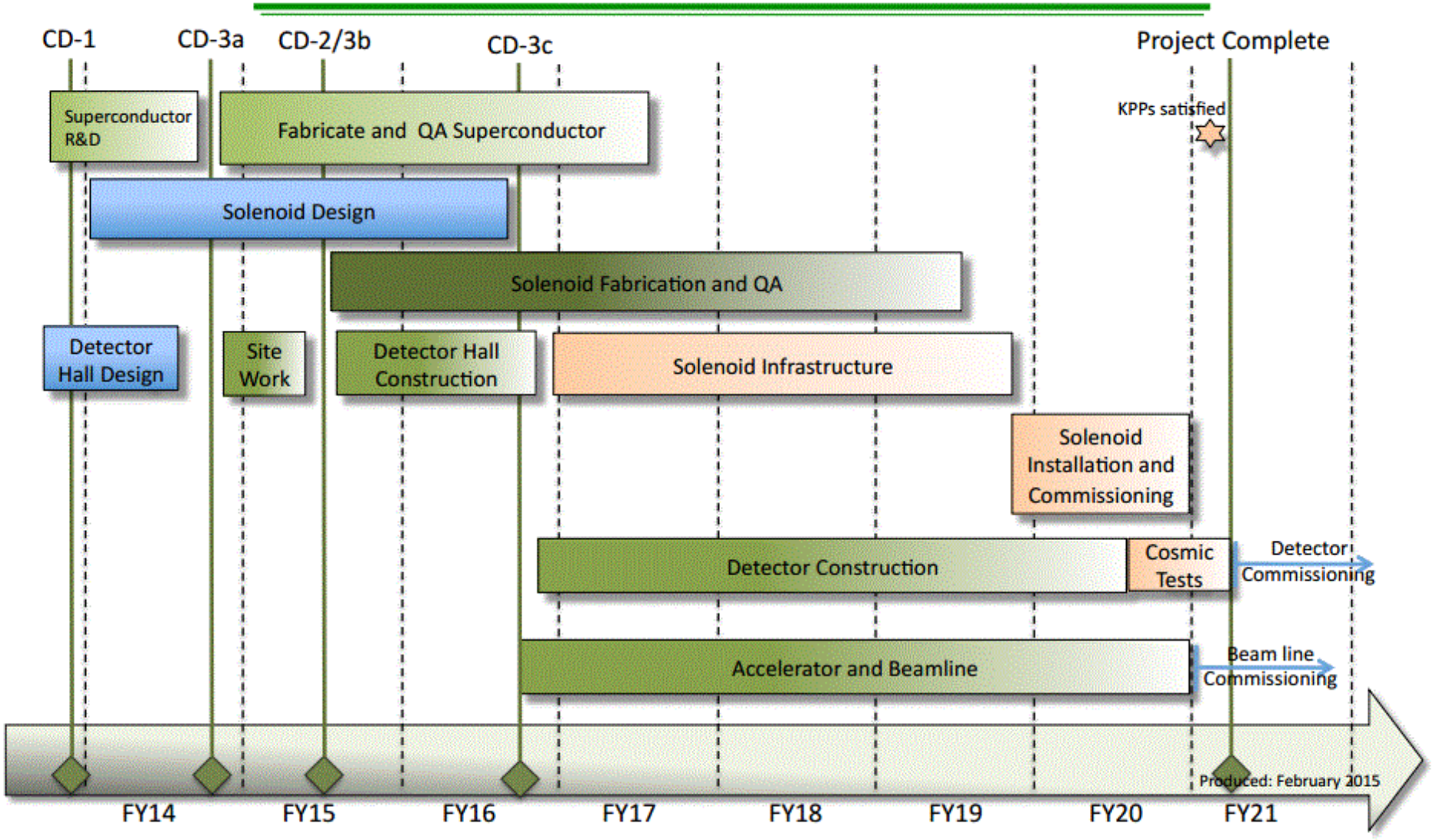
Magnets

- First TS prototype module in hand …and in testing

Buildings

- Beamline is under construction
- Broke ground on the detector building last week!

Global Timeline



Summary

- Mu2e will be a very sensitive search for new physics in CLFV
- Method is muon to electron conversion in field of Al nucleus:

$$\mu^- + N \rightarrow e^- + N$$

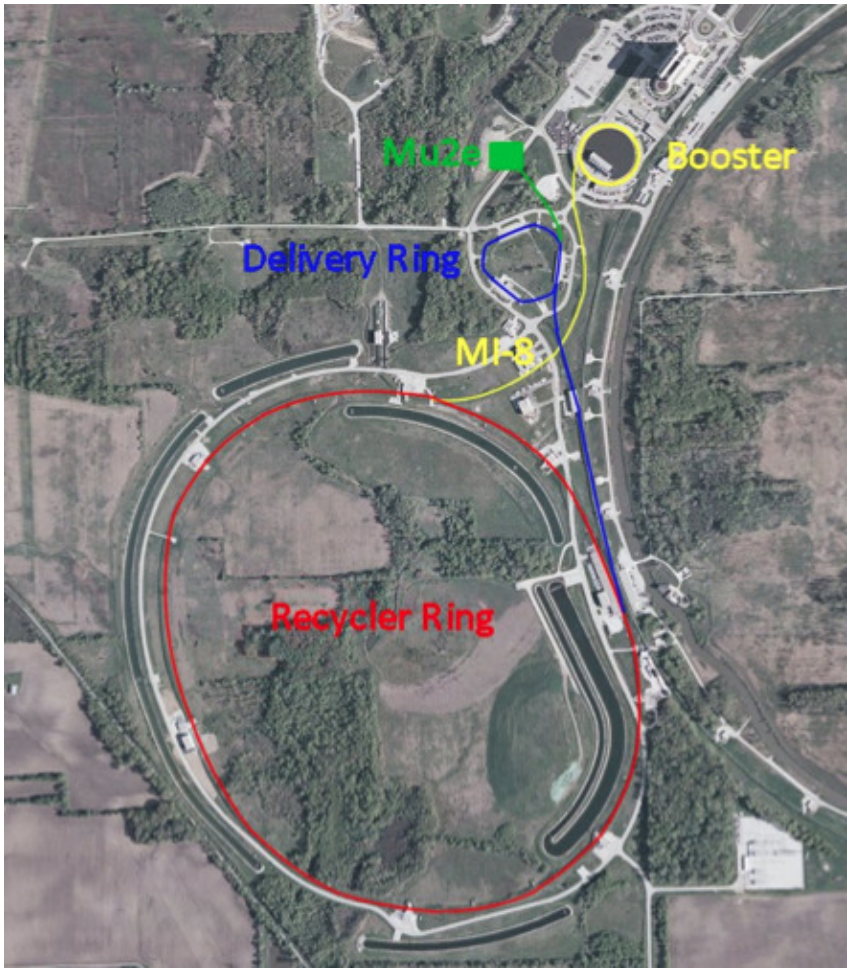
- Ultimate expected sensitivity (10^{20} POT, 3y run):
  - Target limit: $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL
  - Factor 10^4 improvement over current limit!
  - Discovery sensitivity: $R_{\mu e} >$ few $\times 10^{-16}$

- Mu2e design and construction is proceeding, on schedule
- Completed DOE CD-2, 3a → budget approved, baselined
- Operations starting in 2021

Backup

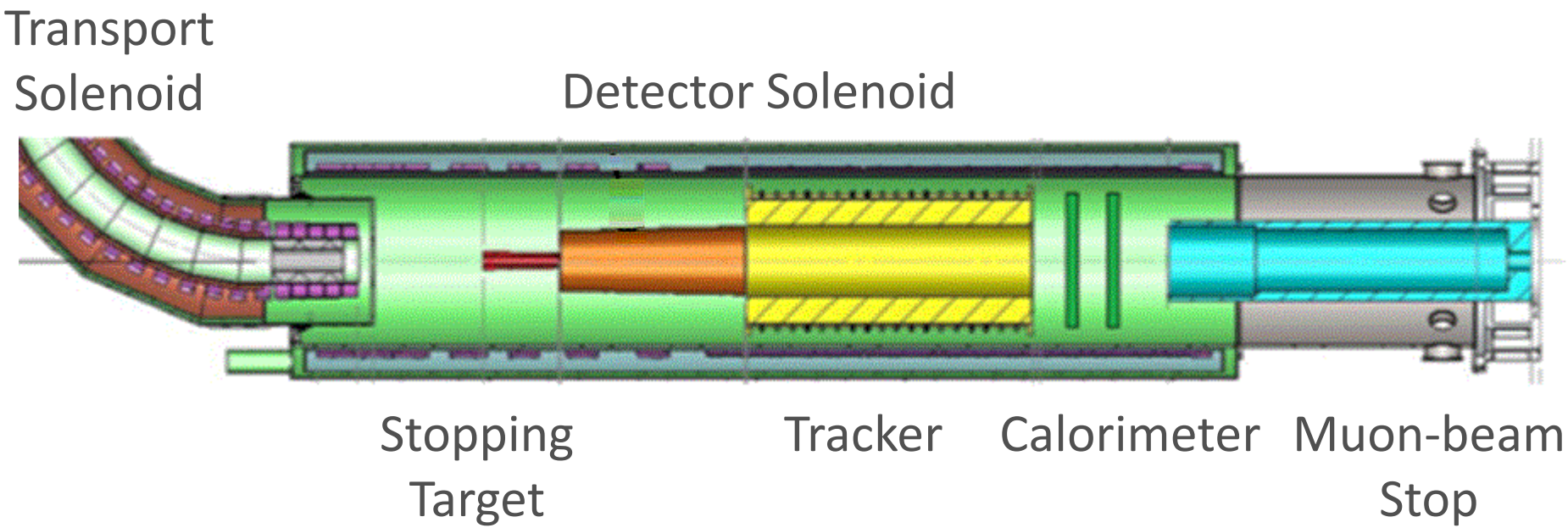
Beamline

- Fermilab is ideal for mu2e
- Repurposing much of the Tevatron anti-proton beamlines for 8 GeV protons
- New muon campus
- Booster produces pulses of $4x10^{12}$ 8-GeV protons
- Recycler 4 bunches 10^{12}
- Delivery ring many bunches of $3x10^{7}$
- 8 kW of protons
- Will run with Nova



The Detector

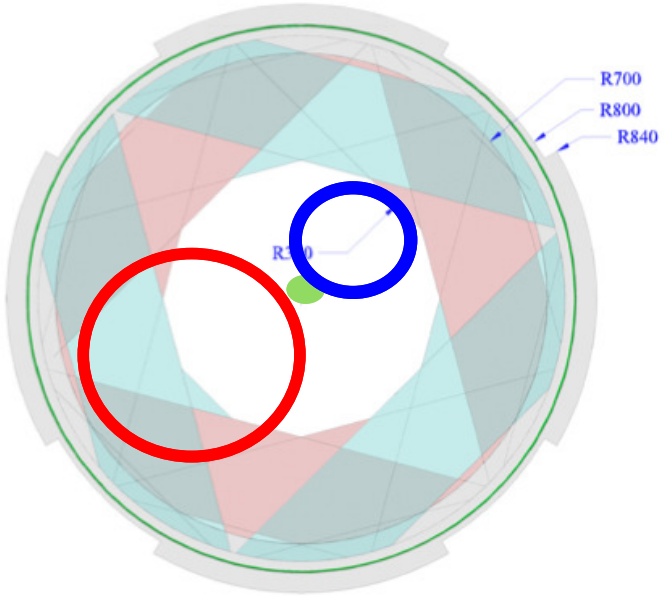
- Observe 105MeV electrons with high efficiency, good resolution
- Reject anything out of time, DIO, cosmic rays

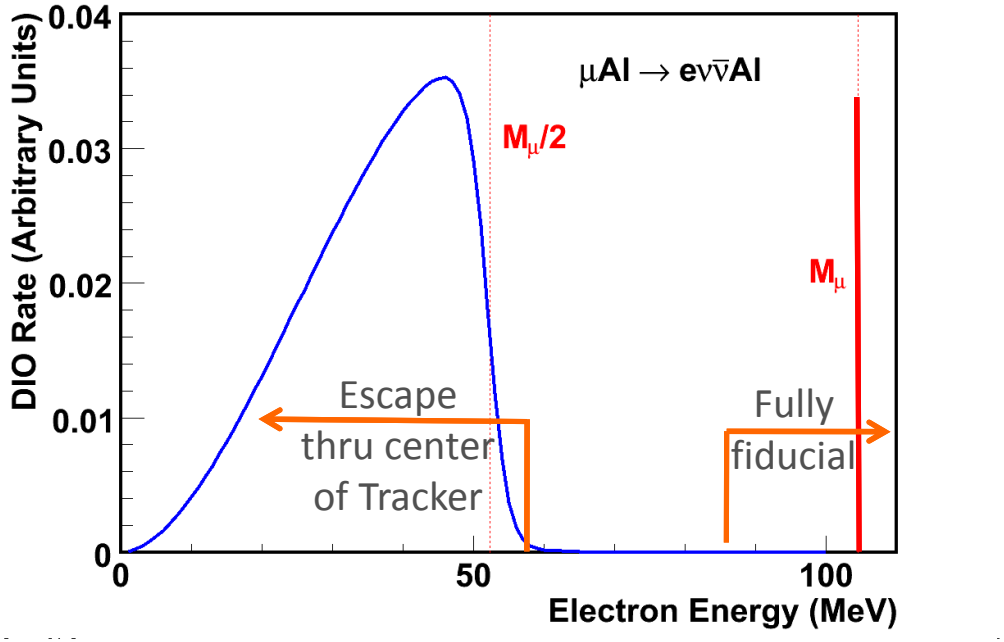


- All surrounded by the cosmic ray veto!

Tracker DIO Rejection

- View along beam shows uninstrumented inner 38cm

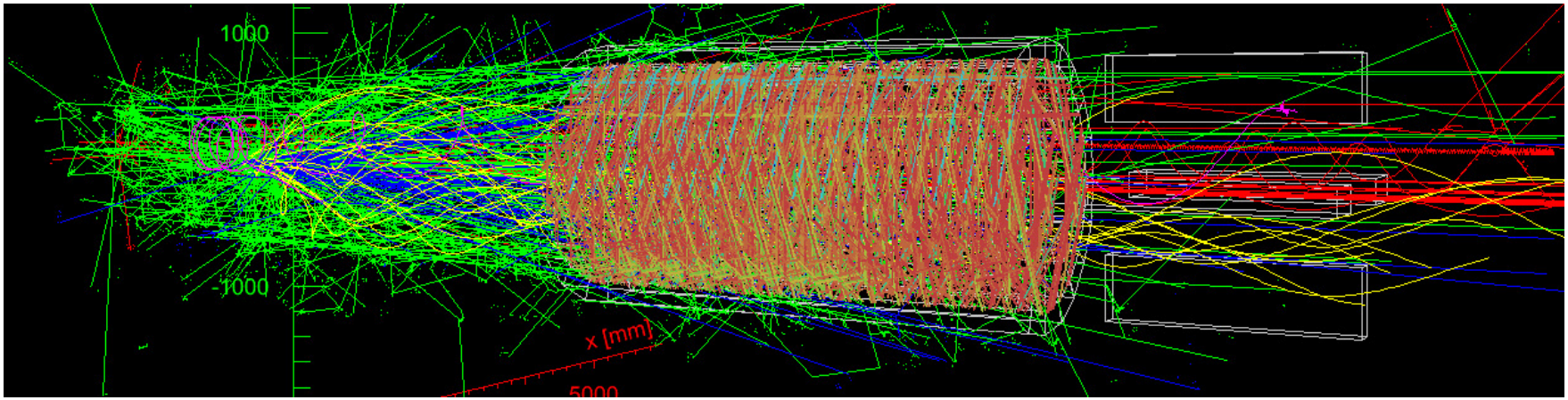




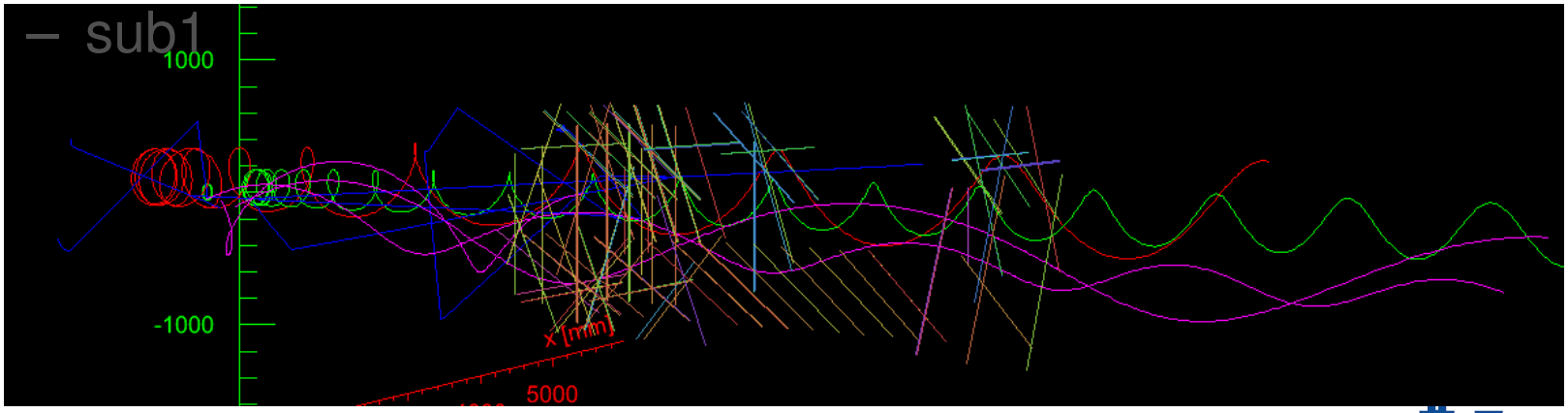
- Rejects 99% of DIO
- Blind to muon beam

Tracker Timing

- Activity in one microbunch (700ns data collection window)

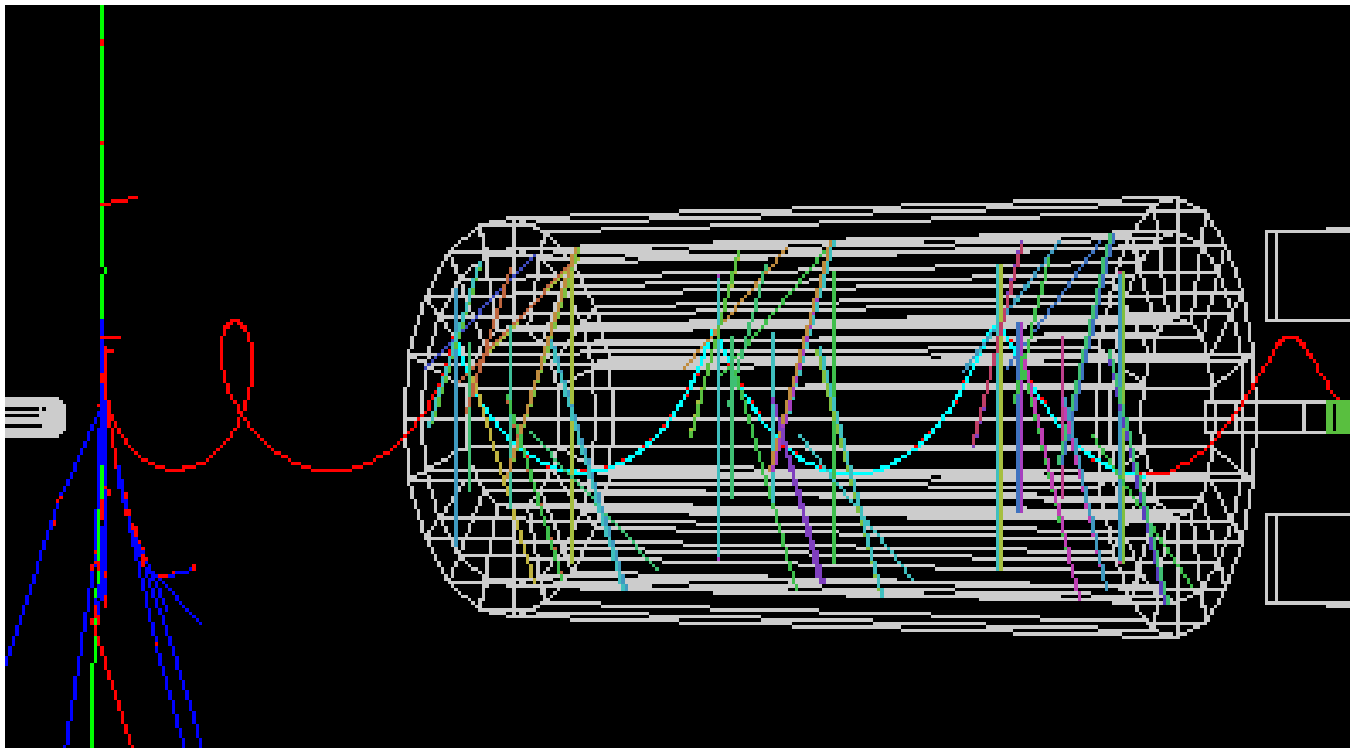


- Activity within 50ns of signal electron



Cosmic Ray Veto

- Cosmic rays can produce 105 MeV electrons as decay, delta rays or bremsstrahlung followed by conversion pair



- Would expect about 1 per day - CRV must reject 99.99%
- Final performance: 0.1 events expected in the whole run